A mantle plume beneath California? The mid-Miocene Lovejoy flood basalt, northern California

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ABSTRACT

The Lovejoy basalt represents the largest eruptive unit identified in California, and its age, volume, and chemistry indicate a genetic affinity with the Columbia River Basalt Group and its associated mantle-plume activity. Recent field mapping, geochemical analyses, and radiometric dating suggest that the Lovejoy basalt erupted during the mid-Miocene from a fissure at Thompson Peak, south of Susanville, California. The Lovejoy flowed through a paleovalley across the northern end of the Sierra Nevada to the Sacramento Valley, a distance of 240 km. Approximately 150 km^3 of basalt were erupted over a span of only a few centuries. Our age dates for the Lovejoy basalt cluster near 15.4 Ma and suggest that it is coeval with the 16.1–15.0 Ma Imnaha and Grande Ronde flows of the Columbia River Basalt Group. Our new mapping and age dating support the interpretation that the Lovejoy basalt erupted in a forearc position relative to the ancestral Cascades arc, in contrast with the Columbia River Basalt Group, which erupted in a backarc position. The arc front shifted trenchward into the Sierran block after 15.4 Ma. However, the Lovejoy basalt appears to be unrelated to volcanism of the predominantly calc-alkaline Cascade arc; instead, the Lovejoy is broadly tholeiitic, with trace-element characteristics similar to the Columbia River Basalt Group.

Association of the Lovejoy basalt with mid-Miocene flood basalt volcanism has considerable implications for North American plume dynamics and strengthens the thermal "point source" explanation, as provided by the mantle-plume hypothesis. Alternatives to the plume hypothesis usually call upon lithosphere-scale cracks to control magmatic migrations in the Yellowstone–Columbia River basalt region. However, it is difficult to imagine a lithosphere-scale flaw that crosses Precambrian basement and accreted terranes to reach the Sierra microplate, where the Lovejoy is located. Therefore, we propose that the Lovejoy represents a rapid migration of plume-head material, at ~20 cm/yr to the southwest, a direction not previously recognized.

Keywords: mantle plume, Yellowstone, Lovejoy basalt, flood basalt, Columbia River basalt.

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INTRODUCTION

Mid-Miocene volcanism in the northern Sierra Nevada occurred during a period of widespread and voluminous magmatism in the western United States (Christiansen et al., 2002; Dickinson, 1997). To the north of the Sierra Nevada, the 17–14 Ma Columbia River basalt and the Steens basalt erupted in great volumes on the Columbia and Oregon Plateaus behind the ancestral Cascade arc. At 16 Ma, the McDermitt caldera in northern Nevada was active and formed the oldest known of a succession of silicic calderas and basaltic flows that track northeastward along the eastern Snake River Plain toward the Yellowstone caldera (Armstrong et al., 1975; Rodgers et al., 1990) (Fig. 1A). Extending southward from the McDermitt caldera, eruptions occurred in the northern Nevada rift, an extensional basaltic dike complex located in the Basin and Range Province (Zoback et al., 1994). All of these eruptions occurred inboard of the ancestral Cascades arc (Dickinson, 1997). In the northern Sierra Nevada, the Lovejoy basalt erupted (Figs. 1A and 1B), forming California's most widespread basalt flow (Wagner et al., 2000). In this paper, we present geologic, geochronologic, and geochemical evidence that the Lovejoy basalt is genetically related to the Columbia River Basalt Group, but that the Lovejoy basalt erupted in a forearc, not backarc, tectonic setting (see Busby et al., 2008). The association of the Lovejoy basalt with mid-Miocene flood basalt activity has considerable implications for North American plume dynamics and strengthens the thermal "point source" explanation, as provided by the mantle-plume hypothesis.

The estimated total volume of the Lovejoy basalt is ~150 km^3 (Durrell, 1987; Wagner et al., 2000), roughly one-quarter the volume of the average individual flow in the Columbia River Basalt Group. However, individual flows of the Lovejoy basalt represent a significant volume of erupted material in comparison with major historic lava flows. Based on the distribution of erosional remnants of Lovejoy basalt, individual flows may have erupted with an estimated volume of up to 75 km^3. For comparison, the Laki eruption of 1783–1785, the largest basaltic eruption in recorded history, only produced a total volume of 14.7 km^3 of basalt from a fissure in central Iceland (Self et al., 1997). Further, new paleomagnetic results from Coe et al. (2005, p. 700) indicate that "almost 90% of the Lovejoy type section was erupted… within a few centuries." The rapid eruption of such a significant volume of lava further argues against the Lovejoy being related to Cascade arc-volcanism, and in favor of a relationship to Columbia River Basalt Group flood volcanism.

The Lovejoy basalt is geochemically similar to the Columbia River Basalt Group (Doukas, 1983; Siegel, 1988; Wagner et al., 2000), but it was previously considered to be Eocene in age (Durrell, 1959b). Recently published age dates (Page et al., 1995) and new dating presented here shows that the Lovejoy basalt erupted at ca. 15.4 Ma, and is thus coeval with the 16.1–15 Ma Imnaha and Grande Ronde basalts, which are the volumetrically dominant eruptive units of the Columbia River Basalt Group. These data suggest that the Lovejoy basalt may share a common parentage with the Columbia River Basalt Group, and that the effects of flood basalt volcanism were expressed much further to the southwest than previously recognized.

In this paper, we summarize previous work concerning the Lovejoy basalt and present our new field observations and interpretations, followed by a discussion of its physical volcanology. We additionally present new geochronological data and geochemical results. Finally, we discuss possible implications of the Lovejoy basalt for plume dynamics.

OVERVIEW OF THE LOVEJOY BASALT

The Lovejoy Formation (hereinafter the Lovejoy basalt) was named by Durrell (1959b) after Lovejoy Creek, a tributary located adjacent to a principal occurrence of the basalt. It is a distinctive, black, dense, dominantly aphyric, low-MgO basalt that occurs as isolated exposures and remnants in a NE-SW–trending band extending from the Honey Lake fault scarp across the northern end of the Sierra Nevada into the Sacramento Valley (Fig. 1B), a distance of ~240 km. Durrell (1987) estimated that the Lovejoy basalt originally covered a surface area of 130,000 km^2, although the pattern of known outcrops and reported subsurface occurrences (Durrell, 1959b; Siegel, 1988; Wagner et al., 2000) suggest that the aerial extent of the Lovejoy basalt may be only half that extensive. New mapping performed for this study demonstrates that the basalt reaches a maximum exposed thickness of ~245 m at Stony Ridge, located south of Thompson Peak in the Diamond Mountains (Fig. 1B), where up to 13 individual flows can be recognized. Previous and new mapping indicates that the basalt was broadly channelized within granitic basement and flowed 30 km south from the vent to its type locality at Red Clover Creek, before bending to the southwest and flowing 65 km to the ancestral Sacramento Valley. There the Lovejoy basalt either ponded or inflated and formed very thick flows that flooded a basin the width of the present-day Sacramento Valley.

Outcrops of the Lovejoy basalt display a characteristic irregular jointing and are highly fractured, although they may exhibit well-formed columnar jointing. Individual flows in the Diamond Mountains may be up to 45 m thick, and they form an alternating sequence of cliffs and talus slopes, where the upper surfaces of the talus slopes mark the boundary between individual flows. The basalt is aphyric, except for a plagioclase-phyric upper flow unit in the Diamond Mountains, relatively glassy (up to 30%–40%), and is composed of a groundmass of microcrystalline plagioclase, olivine, and glass, with lesser pyroxene and Ti-Fe oxides (Fig. 2A). It exhibits an intersertal groundmass texture, and glass in the groundmass is frequently altered. Ubiquitous phenocrysts of plagioclase were identified only in an uppermost flow of the basalt at Stony Ridge and Red Clover Creek, and locally at Thompson Peak (Fig. 2B). This flow additionally contains minor olivine and xenocrysts of garnet at one location at Red Clover Creek.

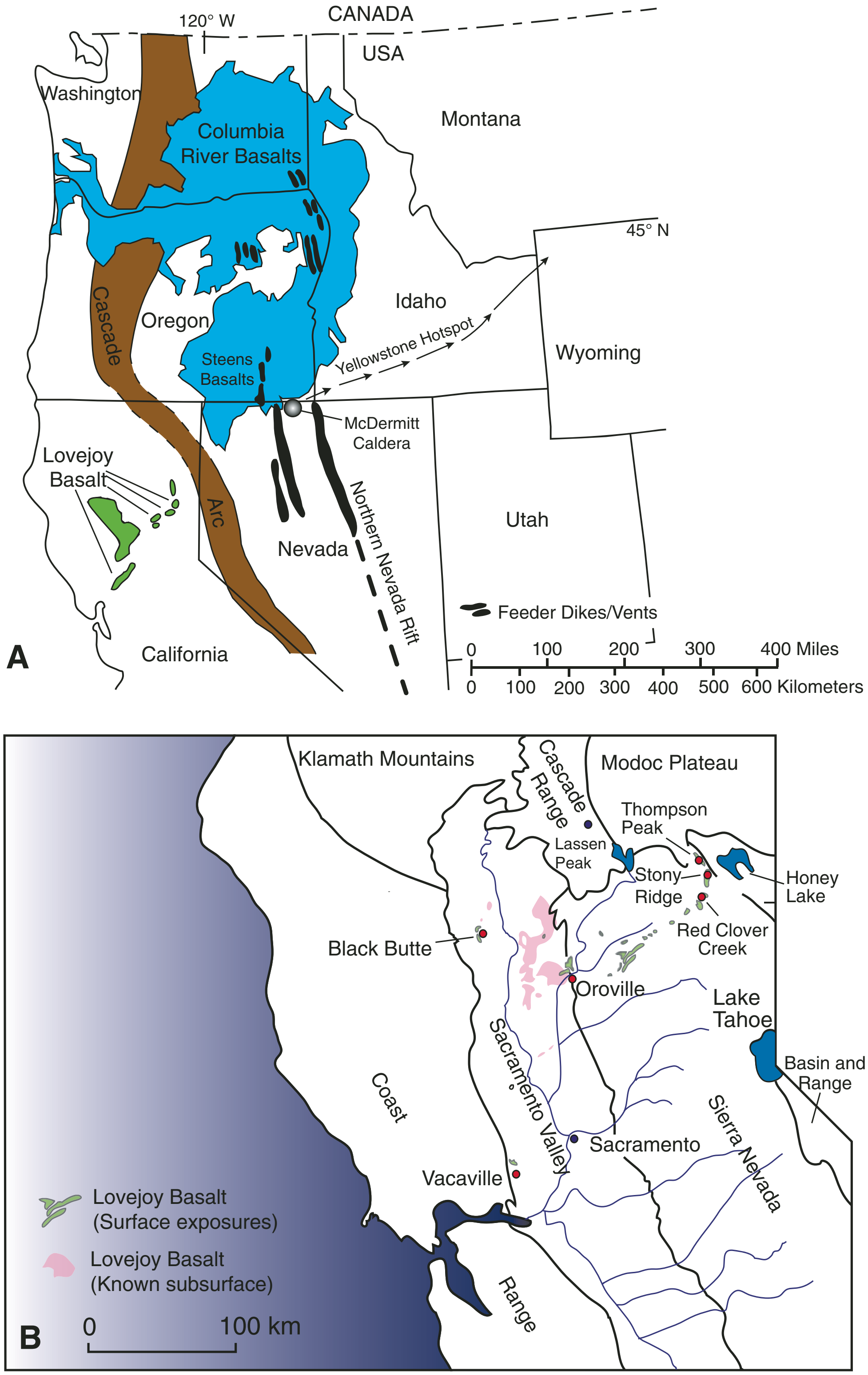


Figure 1. (A) Volcanic provinces of the western United States active during the mid-Miocene period. (Modified from Durrell, 1959b; Pierce and Morgan, 1992; Christiansen and Yeats, 1992; Dickinson, 1997 *as in* Wagner et al., 2000; and Camp and Ross, 2004 *as in* Coe et al. 2005.). (B) Regional map of northern California showing physiographic provinces and principal occurrences of the Lovejoy basalt. (Modified from Durrell, 1959b, 1987; Wagner et al., 2000.)

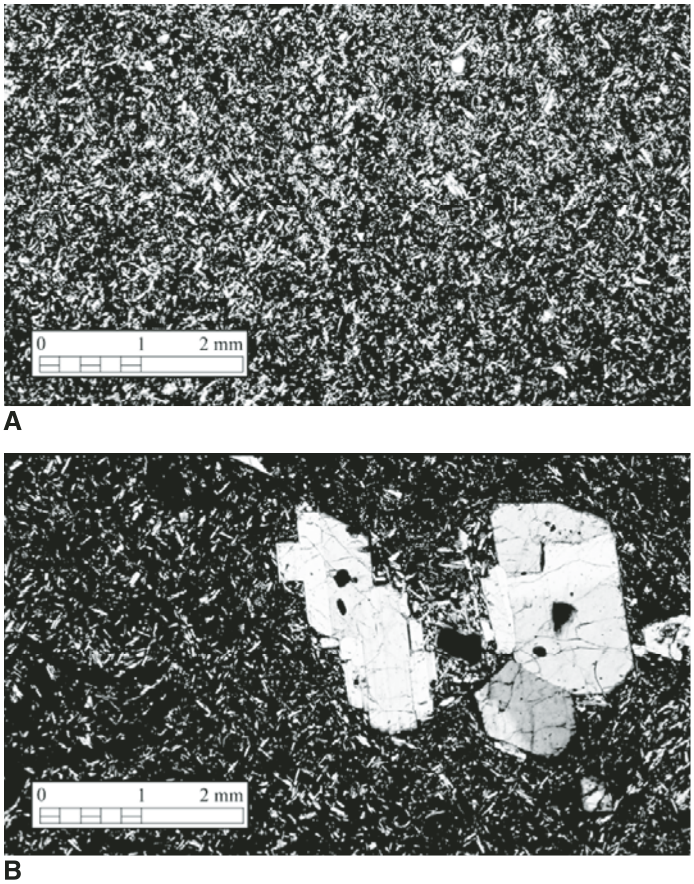


Figure 2. The Lovejoy basalt in cross-polarized light. (A) Sample 02LJRCC1. Flow 1 at Red Clover Creek; microcrystalline groundmass of plagioclase, olivine, clinopyroxene, Ti-Fe oxides, and glass. (B) Sample 02LJRCC8. Flow 8 at Red Clover Creek; phenocrysts of plagioclase common to the uppermost flow of the Lovejoy basalt in a microcrystalline groundmass.

PREVIOUS WORK ON THE LOVEJOY BASALT

Durrell (1959b) and others, including Doukas (1983), Roberts (1985), and Siegel (1988), have correlated many of the principal localities of the Lovejoy basalt. While Durrell (1959b, 1987) believed that the source of the Lovejoy basalt was located to the east of the Honey Lake fault scarp, Roberts (1985) and Wagner et al. (2000) hypothesized that the source of the Lovejoy basalt might have been a fissure extending south from Thompson Peak that formed as a precursor to the modern Honey Lake fault (Fig. 1B).

The age of the Lovejoy basalt has been widely disputed since its designation as a stratigraphic unit. Based on field relations of the basalt, Durrell (1959b) concluded that the Lovejoy basalt is Eocene in age. Subsequent K-Ar dating (Dalrymple, 1964; Siegel, 1988; Wagner and Saucedo, 1990) indicated that it is actually Miocene in age. Of 15 K-Ar age determinations referred to by Wagner et al. (2000), nine yielded dates between 14 and 17 Ma. However, K-Ar dates for the basalt range from 3.6 to 18.5 Ma (Page et al., 1995), and one date of 24.4 ± 0.6 Ma was reported by Dalrymple (1964). Three dates averaging 15.9 Ma were reported for the Lovejoy basalt by Page et al. (1995) using the $^{40}Ar/^{39}Ar$ step-heating method, although the analytical data and age spectra were not presented.

Previous geochemical investigations of the Lovejoy basalt (e.g., Doukas, 1983; Roberts, 1985; Siegel, 1988) have focused on characterization and correlation of the principal flows. Doukas (1983) and Siegel (1988) additionally carried out limited trace-element analyses of the Lovejoy basalt, and compared the Lovejoy to other rock suites, most notably the Columbia River Basalt Group. Siegel (1988) hypothesized that the two units might have a similar mode of origin, though he believed the Lovejoy basalt to be either Eocene or late Oligocene in age, significantly older than the Miocene Columbia River Basalt Group.

The type locality for the Lovejoy basalt was designated by Durrell (1959b) as Red Clover Creek (Fig. 1B), located ~12 km to the north of Portola, California. Multiple interpretations of the stratigraphy and structure for Red Clover Creek have been made by previous researchers, most notably Durrell (1959a, 1959b), Wagner et al. (2000), and Grose (2000). Durrell interpreted the Lovejoy basalt as an Eocene unit emplaced as a sequence of lava flows confined to a broad river valley. He interpreted all other Tertiary units at Red Clover Creek to be younger than the basalt, where each unit was deposited as a subhorizontal sheet over subdued topography and "separated from the next by faulting and erosion" (1959b, p. 182); these younger units included (in ascending order above the Lovejoy basalt) the Ingalls andesite breccia, rhyolitic tuff of the Delleker formation, and the Bonta andesite breccia.

Wagner et al. (2000) reinterpreted the stratigraphy of the Red Clover Creek area in order to reconcile Durrell's map relations with radiometric dating of the Tertiary formations. The Delleker tuff, which lies up-section from the Lovejoy basalt, has been variously dated as 22.8 ± 0.4 Ma (Dalrymple, 1964), and 30.08 ± 0.06 Ma (Siegel, 1988), while the accepted age for the Lovejoy basalt is now 15–16 Ma (Page et al., 1995; Wagner et al., 2000; this paper). Wagner et al. (2000 postulated that after deposition of the Delleker tuff, it was eroded to leave an adjacent valley, which was then filled by the Lovejoy basalt. This would explain preservation of the Delleker tuff topographically higher than the younger basalt. Most recently, Grose (2000) found that Durrell's Ingalls and Bonta units were unrecognizable as distinct formations and reclassified the breccias as one lithofacies unit.

FIELD RELATIONS AND NEW INTERPRETATIONS

We present a new interpretation of the geology of the type locality of the Lovejoy basalt at Red Clover Creek (Fig. 3). This is followed by new field results and interpretations from the inferred vent area at Thompson Peak, the most proximal flow section at Stony Ridge, and vent-distal localities at Table Mountain, Black Butte, and Putnam Peak.

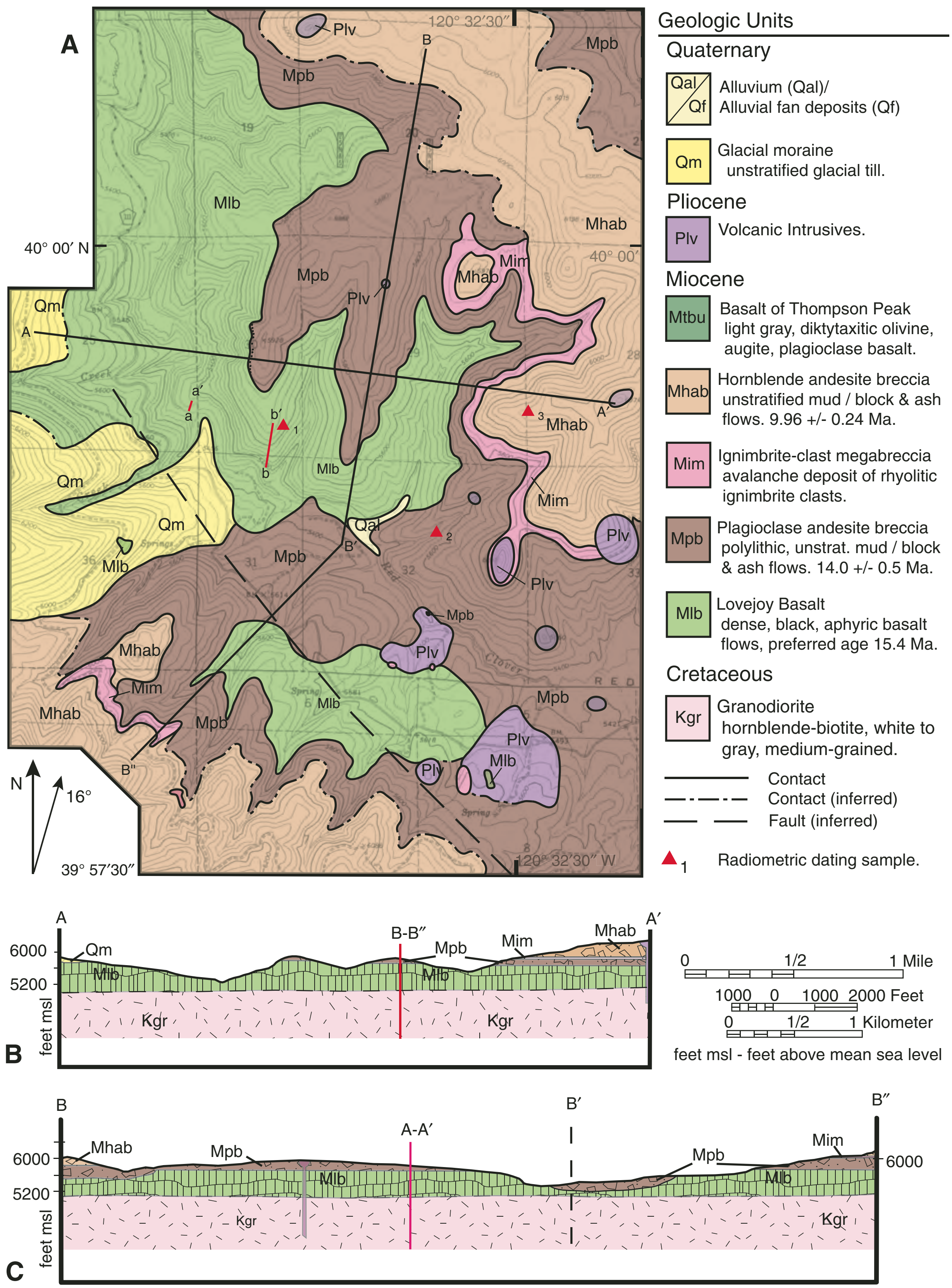


Figure 3. (A) Geologic map of Red Clover Creek and stratigraphic cross sections A–A′ (B) and B–B′–B″ (C) through Red Clover Creek.

TABLE 1. LITHOLOGIC DESCRIPTIONS OF TERTIARY STRATIGRAPHY OVERLYING TH E LOVEJOY BASALT AT RED CLOVER CREEK

Rock name $^{40}Ar/^{39}Ar$ age	Field characteristics	Thin section characteristics	Contact relations with underlying unit	Interpretations
Hornblende-andesite breccia 9.96 ± 0.24 Ma plagioclase	Massive, forms crags similar in outcrop to plagioclase-andesite breccia but generally lighter in color. Poorly sorted angular to subangular clasts dominantly monomict in muddy to sandy or ash matrix. Clasts porphyritic with blades or glomerocrysts of hornblende to 1 cm, lesser plagioclase. Basal 20 m contain sparse clasts of plagioclase andesite, likely reworked from underlying plagioclase-andesite breccia.	Dominant clast type contains hornblende phenocrysts or glomerocrysts to 1 cm in glassy matrix. 1%–2% Fe-Ti oxides. Plagioclase phenocrysts to 2–3 mm. Higher degree of crystallinity than dominant clasts in the plagioclase-andesite breccia.	Gradational, interstratified contact with the plagioclase-andesite breccia. The gradational zone appears to be a minimum of 20 m thick, in which sparse, less than 4-m-thick, laterally noncontinuous layers of the plagioclase-andesite breccia are interstratified with the dominant hornblende-andesite deposits.	Interpreted as primary block-and-ash-flow deposits conformably overlying the plagioclase-andesite breccia and, locally, the ignimbrite clast megabreccia. The plagioclase-andesite breccia lenses interstratified with in the basal 20 m of the unit are likely reworked deposits of the plagioclase-andesite unit that were eroded and resedimented during deposition of the hornblende-andesite breccia.
Ignimbrite clast megabreccia 22.8 ± 0.4 Ma (Dalrymple, 1964) 30.08 ± 0.06 Ma (Siegel, 1988)	Present on north side of Red Clover Creek as 0–20-m-thick unit of isolated tuff clasts and blocks (10 cm–3 m) derived principally from two different rhyolitic ignimbrite units as follows: BUFF TO PALE PINK, pumice poor, unwelded to weakly welded sanidine quartz plagioclase tuff (Table 2, sample TbrRCC1). No mafic phenocryst phase. LIGHT GRAY WITH YELLOW PUMICE, unwelded, biotite sanidine plagioclase tuff with minor quartz (Table 2, sample TbrRCC2). Pumice <1 cm, crystal poor relative to matrix. Abundant, small biotite.	BUFF TO PALE PINK, ground-mass of relatively fresh glass, contains small % Fe-Ti oxides. Some broken bubble wall shards. LIGHT GRAY, unwelded with abundant biotite to 1 mm.	Conformably overlies the plagioclase-andesite breccia on north side of Red Clover Creek.	
Plagioclase-andesite breccia 14.0 ± 0.5 Ma whole rock	Massive, up to 180 m thick. Forms weathered black crags with no recognizable bedding or structure. Poorly sorted angular to subangular clasts dominantly polymict in muddy to sandy matrix with lesser layers of monomict clasts in ash matrix, increasingly monomict up-section. Clasts are cm to m scale. No observed clasts of Lovejoy basalt. MUDDY TO SANDY MATRIX deposits are dominantly clasts of dense to scoriaceous plagioclase andesite (80%–95%) with lesser clasts of basaltic andesite to dacite, granitic rocks, and rhyolitic tuff. Basal few meters contain cobbles interpreted as accidental clasts. Restricted lateral and vertical variation of clasts up-section. ASH MATRIX deposits are composed of ash-sized crystals and rock fragments identical to plagioclase-andesite blocks. Monomict, increases in thickness and frequency up-section.	Dominant clast type contains plagioclase phenocrysts (20%–25%) up to 0.5 cm, and lesser clinopyroxene and orthopyroxene in glassy groundmass. MUDDY TO SANDY MATRIX deposits matrix of silt to sand and gravel-sized clasts of varying composition. ASH MATRIX deposits matrix of ash-sized crystals and rock fragments identical to dominant plagioclase-rich andesite clasts.	Conformably overlies the upper flow of the Lovejoy basalt outside the modern Red Clover Creek Valley. Forms a buttress unconformity against and locally undercuts beneath the basalt in the modern valley. A previously identified contact (Wagner et al., 2000) on the north side of Red Clover Creek appears to show Lovejoy basalt conformably overlying breccia. However, there is no baked horizon present in breccia or quenched margin in bounding basalt. A vertical contact between breccia and Lovejoy basalt ~20 m west shows breccia filling the irregular surface formed by columns of basalt. Jointing in the basalt is perpendicular to the contact. (Fig. 4B). No faults, indications of offset, or fault features were observed between the plagioclase-andesite breccia and Lovejoy basalt.	Interpreted as a series of volcanic mudflow deposits with interstratified block-and-ash-flow tuffs (ash matrix). The interstratification suggests that eruptions from the source volcano occurred coeval with emplacement of the mudflow deposits, representing eruption-fed lahars. The unit is interpreted as paleocanyon fill cut into and locally undercut below the Lovejoy basalt where present within the modern Red Clover Creek Valley. Once the paleocanyon had filled, the lahars and block and ash flows spilled out over the level plateau formed by the upper flow unit of the Lovejoy basalt and were deposited conformably. Jointing in the Lovejoy basalt within the modern Red Clover Creek Valley is perpendicular to the contact with the plagioclase-andesite breccia, indicating that the Lovejoy did not cool against the breccia, but was in place prior to emplacement of the breccia.

Type Locality at Red Clover Creek

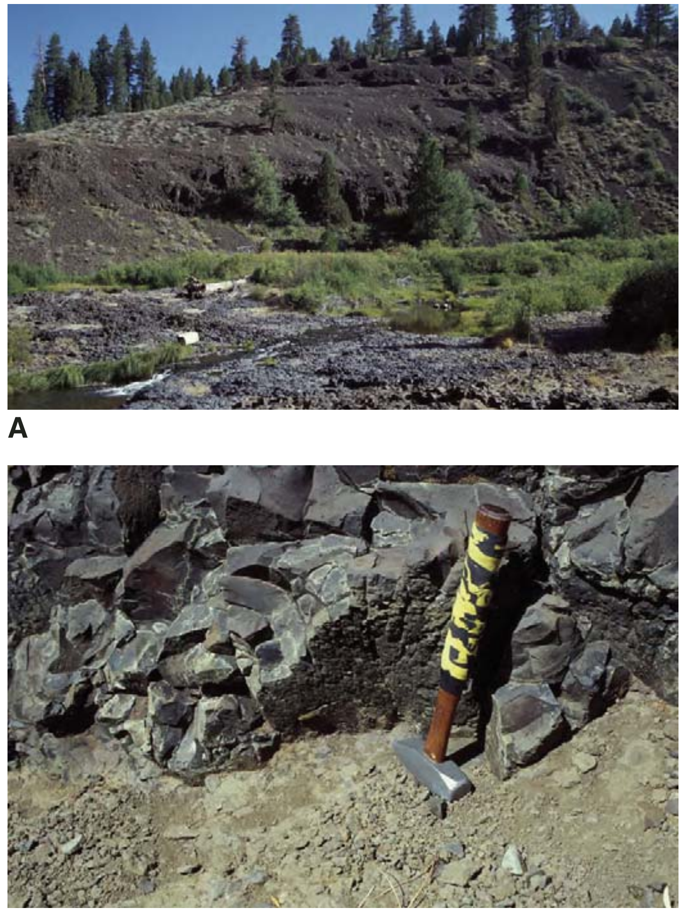
A new interpretation of the structure and stratigraphy of Red Clover Creek is presented in Figure 3 and Table 1. Red Clover Creek is located 30 km from the inferred vent. Our new mapping shows that the Lovejoy basalt is the oldest exposed unit at Red Clover Creek, in agreement with Durrell's (1959a, 1959b) assessment. However, rather than forming a flat surface conformably overlain by and faulted against younger Tertiary units (as proposed by Durrell), we propose that a steep-sided canyon was eroded into the basalt prior to deposition of all other Tertiary strata in the area. Our mapping shows that subsequent Tertiary units first filled the canyon eroded into the Lovejoy basalt, then overtopped the canyon walls and were conformably deposited over the broad plateau formed by the upper flow of the Lovejoy basalt.

The base of the Lovejoy basalt, the lowermost unit at Red Clover Creek, is not exposed at this location, and its substrate is unknown, but it is assumed to overlie Cretaceous batholithic rocks of the Sierra Nevada as it does at Stony Ridge. We recognize eight individual flows of the Lovejoy basalt at Red Clover Creek (Figs. 4A and 5B). The basalt is aphyric except for the uppermost, plagioclase-rich lava flow, also identified at Stony Ridge.

After emplacement of the Lovejoy basalt, erosion created a steep-walled canyon cut into the basalt. A plagioclase-andesite breccia (closely corresponds to mapped distribution of Ingalls formation of Durrell, 1959a) filled this canyon and subsequently spilled over onto the plateau formed by the upper flow of the Lovejoy basalt as a series of volcanic debris flows and lesser block-and-ash flows with a total thickness up to 180 m thick. We obtained a $^{40}Ar/^{39}Ar$ date of 14.0 ± 0.5 Ma for this unit from an apparent flow-front breccia. We interpret the complex contact relations between the Lovejoy basalt and overlying plagioclase-andesite breccia at Red Clover Creek to include a buttress unconformity where the breccia lies against (Fig. 4B) and locally undercuts beneath the Lovejoy basalt in the modern Red Clover Valley, and a conformable contact where it overlies the upper flow of the basalt outside of the present-day valley walls (Figs. 3 and 6; Table 1). This interpretation stands in contrast to Durrell's (1959a) interpretation that the mapped equivalent of the plagioclase-andesite breccia, the Ingalls formation, was deposited as a sheet and then faulted into place against the basalt. We were unable to identify any faults at the contacts between the Lovejoy basalt and the plagioclase-andesite breccia, nor did we find any indication of fault offset, fault planes, slickensides, or fault gouge.

An ignimbrite-clast megabreccia is present as a 0–20-m-thick, locally continuous unit of isolated boulders, blocks, and debris (separated by modern slope wash) that forms a westward-thinning wedge between the underlying plagioclase-andesite breccia and an overlying hornblende-andesite breccia (Table 1). The megabreccia was previously interpreted as in situ Delleker tuff by Durrell (1959a), Siegel (1988), and Wagner et al. (2000). However, on the north side of Red Clover Creek, the ignimbrite clasts appear to be composed of debris from chemically and mineralogically distinct ignimbrites of at least two different compositions (Table 2, TbrRCC1, TbrRCC2). We concluded that the tuff clasts do not represent a primary deposit and have been reworked from their primary source. The clasts were likely emplaced at this location as a landslide deposit. This interpretation reconciles the discrepancy between radiometric dates obtained for tuff clasts originally mapped as Delleker formation (both 22.8 and 30.08 Ma), and for the Lovejoy basalt (15.4 Ma), by allowing separate ignimbrites to have been erupted and deposited at 22 and 30 Ma, then remobilized as landslide blocks after the 15.4 Ma Lovejoy basalt was erupted and buried by the 14 Ma plagioclase-andesite breccia.

Deposition of the ignimbrite-clast megabreccia was followed by deposition of a hornblende-andesite breccia (closely



A

B

Figure 4. (A) The lower four flows of the Lovejoy basalt at the type locality at Red Clover Creek showing prominent cliffs of the basalt alternating with steep talus slopes. (B) Vertical joints of the Lovejoy basalt in contact with the plagioclase-andesite breccia, indicating that the Lovejoy basalt was in place prior to deposition of the breccia and did not cool against the mudflow and block-and-ash-flow deposits.

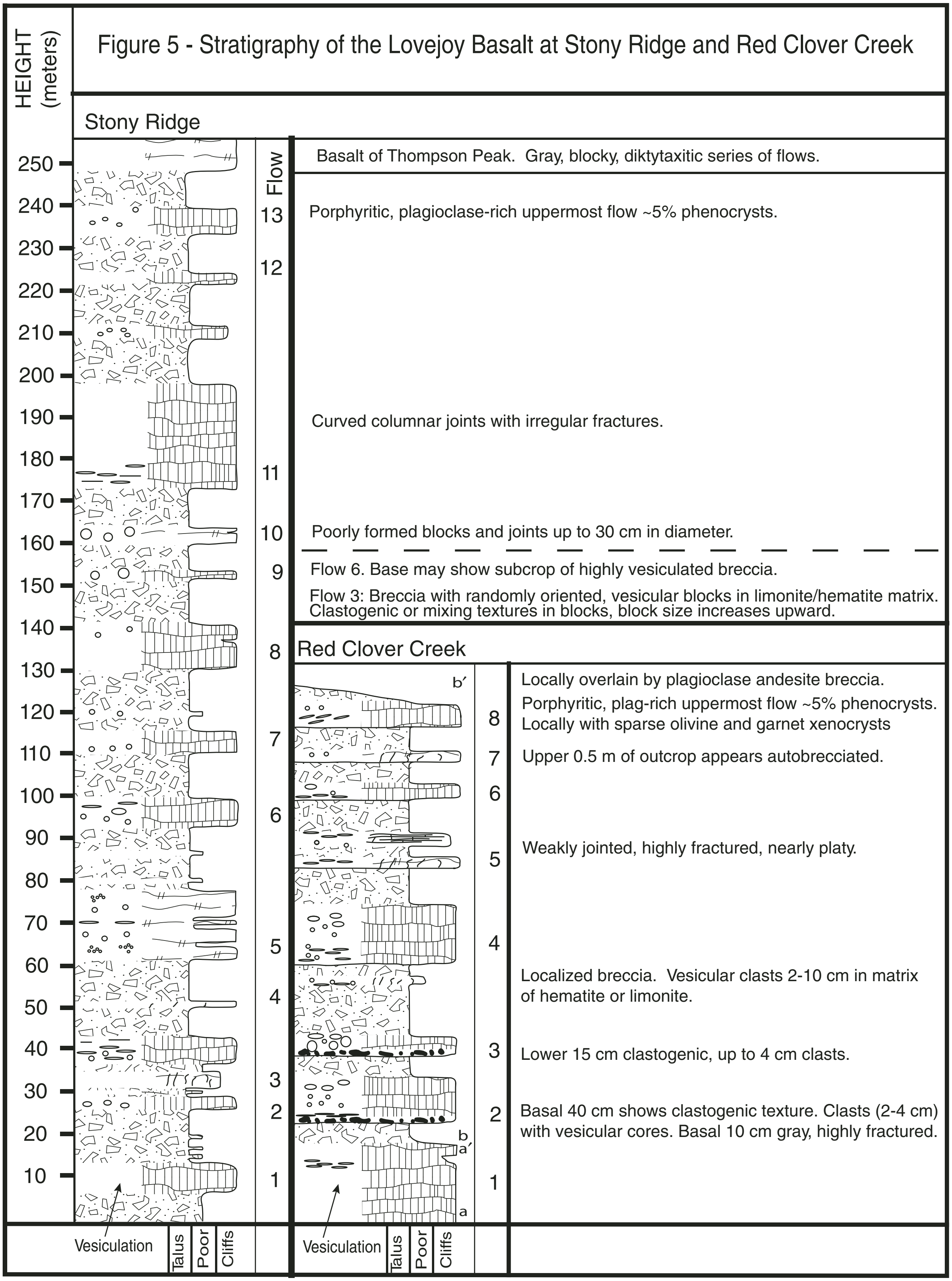


Figure 5. Stratigraphy of the Lovejoy basalt at Stony Ridge and Red Clover Creek.

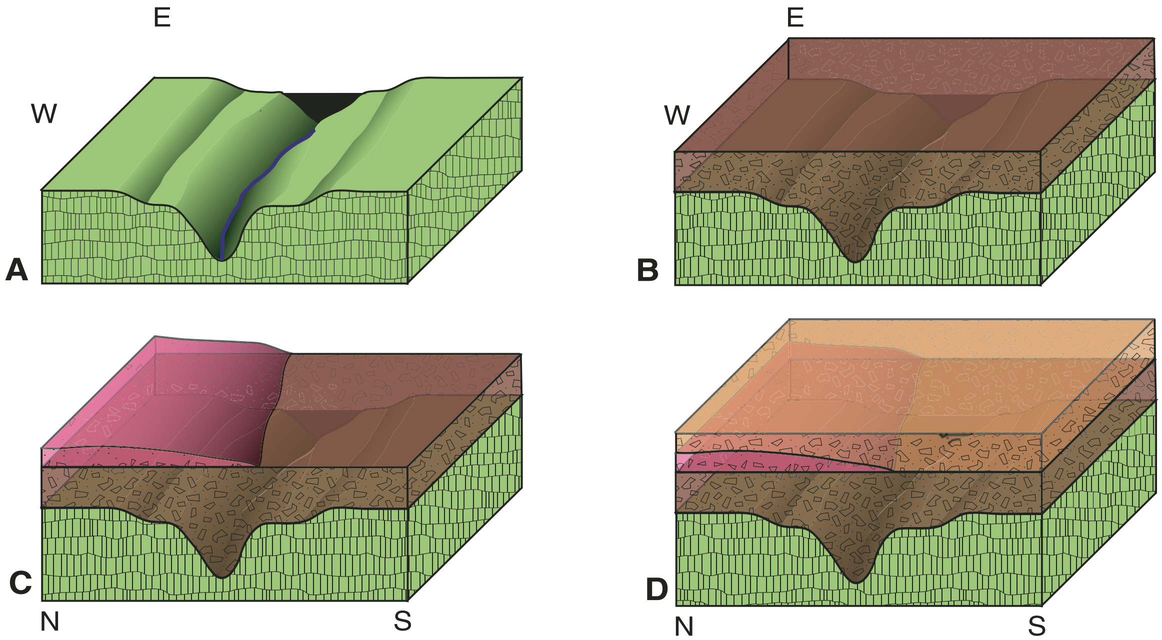


Figure 6. Schematic illustration of the depositional sequence at Red Clover Creek. (A) The Lovejoy basalt was deposited and a steep-walled canyon was eroded into the basalt. (B) A plagioclase-andesite breccia filled the paleocanyon and overtopped the basalt as a series of lahars and block-and-ash flows. (C) A landslide megabreccia of ignimbrite clasts was deposited. (D) A hornblende-andesite breccia was deposited as a series of lahars and block-and-ash flows.

corresponds to mapped distribution of Bonta formation of Durrell, 1959a) (Figs. 3 and 6; Table 1). This unit is a monomict, porphyritic hornblende-andesite breccia up to 150 m thick. We interpret the unit to be composed primarily of primary block-and-ash-flow deposits that conformably overlie the plagioclase-andesite breccia in a gradational and interstratified contact (Fig. 3). We obtained a $^{40}Ar/^{39}Ar$ date of 9.96 ± 0.24 Ma on plagioclase separates from a clast of the hornblende-andesite breccia, which establishes that it is significantly younger than the plagioclase-andesite breccia (Fig. 6). Subsequent stream erosion has formed the modern-day Red Clover Creek Valley.

With the exception of a strand of the Lake Davis fault, which may extend through part of the study area, we found no evidence of any syndepositional or significant postdepositional faulting of any of the Tertiary units at Red Clover Creek. As a result, we attribute all of the complex contact relations between units at the type locality to paleotopographic controls.

Vent and Vent-Proximal Facies at Thompson Peak and Stony Ridge

We identified a ridge located at Thompson Peak, in the Diamond Mountains west of Honey Lake (Fig. 1B), as the source vent for the Lovejoy basalt (Fig. 7). A section of this ridge to the south of Thompson Peak was previously identified by Roberts (1985) and Wagner et al. (2000) as the basalt's potential source. At Thompson Peak, the basalt forms an elongate, NW-SE–trending ridge of nonstratified basalt that is 6.5 km long by up to 1.5 km wide, which we interpret to represent a remnant spatter rampart. The Lovejoy basalt is capped by the 10.1 ± 0.6 Ma (Roberts, 1985) basalt of Thompson Peak, a light gray, diktytaxitic, olivine-augite basalt that forms the upper reaches of Thompson Peak. The Lovejoy basalt at Thompson Peak is bounded by granodiorite basement along the majority of its perimeter. However, the contact between the Lovejoy basalt and basement rocks is generally poorly exposed and does not appear to be diagnostic in determining the relationship between the two units.

At Thompson Peak, there is no indication that the Lovejoy basalt was emplaced as a sequence of sheet flows. However, at one locality along the contact between the Lovejoy basalt and the overlying basalt of Thompson Peak, there is an outcrop of Lovejoy basalt that exhibits conspicuous phenocrysts of plagioclase (Fig. 7, location x). We have identified these phenocrysts in the uppermost flow of the Lovejoy basalt at other locations in the Diamond Mountains (see following). Hooper (1999) indicated that small cones of material may form along restricted areas of dikes in fissure eruptions, representing the waning phases of an eruption as magma supply drops. The phyric outcrop may represent an erosional remnant of a capping flow or spatter accumulation formed during the last eruptive event at the vent.

Agglutinate, scoria, and bomb fragments are visible along the full extent of the ridge at Thompson Peak. Roberts (1985) previously noted the presence of these deposits at one location in what was, at the time, termed the lower basalt of Thompson Peak and suggested it could be a source vent for the Lovejoy

TABLE 2. GEOCHEMICAL ANALYSES OF SAMPLES FROM GEOLOGIC UNITS AT RED CLOVER CREEK

Sample:	BrRCC2a	BrRCC3d	BrfRCC6	BrRCC10a	TbrRCC1	TbrRCC2
Geol. Unit:	Mpb	Mpb	Mpb	Mhab	Mim	Mim
wt% (normalized on a volatile-free basis)						
SiO_2	61.77	64.79	59.10	60.85	76.55	74.75
TiO_2	0.793	0.574	0.866	0.558	0.146	0.253
Al_2O_3	17.62	17.03	17.78	17.99	13.23	14.35
FeO*	5.10	3.89	6.54	5.90	0.88	0.67
MnO	0.117	0.113	0. 132	0.103	0.009	0.075
MgO	1.97	1.69	2.92	2.66	0.00	0.09
CaO	5.38	4.54	6.31	5.96	0.78	0.91
Na_2O	3.99	3.80	3.72	4.10	3.21	3.45
K_2O	2.89	3.33	2.36	1.65	5.16	5.43
P_2O_5	0.366	0.245	0.270	0.225	0.028	0.021
ppm (XRF)						
Ni	5	11	17	20	10	8
Cr	1	7	7	25	3	3
Sc	12	9	16	14	4	5
V	117	75	162	120	8	14
Ba	926	977	871	865	694	870
Rb	74	68	47	31	153	199
Sr	602	540	588	654	106	126
Zr	173	176	140	112	197	306
Y	35	22	22	16	18	25
Nb	8.3	6.9	6.5	4.5	12.3	14.8
Ga	19	20	19	21	18	18
Cu	33	27	29	39	11	9
Zn	107	85	86	87	37	56
Pb	14	15	11	15	30	25
La	28	24	23	16	41	49
Ce	50	51	45	29	67	82
Th	7	6	5	3	29	28

(*continued.*)

basalt. Coalesced spatter with elongate, plastically deformed, and flattened vesicles are common and were likely produced by the weight from accumulating material. Scoria and highly vesiculated bomb fragments up to 30–40 cm in diameter are also present (Fig. 8). Agglutinated clasts are observable on fresh surfaces as mottled, tan, angular to amorphous "blebs" that have been partly reassimilated into the surrounding homogeneous basalt. These deposits appear to represent vent-proximal spatter ramparts. Wolff and Sumner (1999) noted that spatter piles can be diagnostic of the locations of volcanic vents, and the deposits at this location identify Thompson Peak as the source vent of the Lovejoy basalt.

Stony Ridge (Fig. 1B), located 8 km southeast of Thompson Peak, consists of a N-S–trending, gently S-dipping plateau of the Lovejoy basalt measuring 10 km (N-S) by up to 3 km (E-W). At this location, we identified 13 individual lava flows, which represent the largest known number of exposed flows of the Lovejoy basalt (Fig. 5A). The basalt appears to overlie basement rocks along the western edge of Stony Ridge and at lower elevations along the ridge's northern boundary. The contact is poorly exposed, and the granodiorite proximal to the contact is highly weathered. The Lovejoy basalt itself at Stony Ridge is aphyric except for the uppermost flow, which displays the same conspicuous plagioclase phenocrysts that are locally present in the Lovejoy basalt at Thompson Peak below its contact with the overlying basalt of Thompson Peak and in the uppermost flow of the Lovejoy basalt at Red Clover Creek.

Distal Flows in the Ancestral Sacramento Valley

North and South Table Mountains, located north of Oroville, California (Fig. 1B), represent one of the largest erosional remnants of the Lovejoy basalt. North Table Mountain forms a broad, irregularly shaped plateau ~8 km by up to 3.5 km, while South Table Mountain measures ~1.25 km by 3.5 km. In both locations, the Lovejoy basalt may be greater than 100 m thick and appears to be composed of two to three flows, although divisions between flows are difficult to discern due to vegetative cover. A fresh cliff face at the Martin Marietta gravel quarry at North Table Mountain displays well-formed columnar jointing and appears to represent a single flow measuring more than 75 m thick. The basalt at this location is more coarsely crystalline than at locations in the Diamond Mountains. The plagioclase-phyric flow exposed at Stony Ridge and Red Clover Creek is not present at the Table Mountains, and it does not appear to have extended into the ancestral Sacramento Valley. The upper surface of North and South Table Mountains is marked by compressional ridges, discussed further later in this paper.

Two flows of the Lovejoy basalt reached as far west as Black Butte, located west of Orland, California, and as far south as Putnam Peak, located north of Vacaville, California, a distance of 240 km from the vent at Thompson Peak (Fig. 1B). These localities represent the most distal known exposures of the Lovejoy basalt. The flows reach a maximum thickness of ~20 m at Black Butte. Siegel (1988) indicated that the Lovejoy basalt

TABLE 2. GEOCHEMICAL ANALYSES OF SAMPLES FROM GEOLOGIC UNITS AT RED CLOVER CREEK (*continued*.)

	Geochemical analyses of the Lovejoy basalt at Red Clover Creek								Geochemical analyses of the Lovejoy basalt at Stony Ridge										
Flow no.	RCC1	RCC2	RCC3	RCC4	RCC5	RCC6	RCC7	RCC8	SR1	SR2	SR3	SR4	SR5a	SR7	SR8	SR10	SR11	SR12	SR13
wt% (normalized on a volatile-free basis)																			
SiO_2	52.08	52.44	52.44	52.43	51.78	51.96	51.76	52.63	50.97	51.74	52.19	52.02	51.88	51.50	51.79	52.61	52.09	52.10	52.38
TiO_2	2.602	2.581	2.576	2.606	2.603	2.582	2.606	2.299	2.436	2.635	2.606	2.567	2.593	2.616	2.613	2.631	2.597	2.571	2.265
Al_2O_3	14.10	14.24	14.20	14.21	14.05	14.10	14.12	14.79	14.50	14.35	14.18	14.17	14.14	14.24	14.13	14.40	14.26	14.15	14.71
FeO*	12.44	12.04	12.22	12.21	12.62	12.57	12.69	11.69	13.02	12.54	12.17	12.41	12.40	12.74	12.48	11.68	12.36	12.48	11.88
MnO	0.2†7	0.27†	0.26†	0.251	0.26†	0.26†	0.243	0.230	0.236	0.244	0.245	0.241	0.247	0.242	0.244	0.235	0.242	0.245	0.219
MgO	4.19	4.19	4.12	4.12	4.34	4.24	4.25	4.13	4.57	3.88	4.05	4.20	4.16	4.22	4.23	3.79	3.96	4.10	4.25
CaO	7.92	7.86	7.79	7.95	7.99	7.93	8.01	8.20	8.46	8.09	7.91	7.80	7.92	8.05	7.97	8.15	8.08	7.94	8.30
Na_2O	3.39	3.22	3.10	3.07	3.15	3.18	3.12	3.23	2.91	3.23	3.17	3.23	3.17	3.10	3.25	3.24	3.23	3.19	3.15
K_2O	1.77	1.95	2.07	1.94	1.98	1.97	1.98	1.83	1.89	2.01	2.25	2.16	2.26	2.05	2.08	2.04	1.97	2.03	1.90
P_2O_5	1.24†	1.21†	1.22†	1.21†	1.21†	1.21†	1.22†	0.97†	0.997	1.274	1.241	1.206	1.222	1.235	1.225	1.228	1.209	1.194	0.950
ppm (XRF)																			
Ni	13	7	10	8	11	9	10	17	21	10	9	7	7	4	7	7	7	9	18
Cr	15	17	14	14	16	15	16	29	28	14	16	16	13	13	13	12	12	14	32
V	327	337	342	349	343	338	345	339	359	341	330	325	335	343	340	343	336	334	336
Ga	21	16	19	22	21	21	20	19	22	22	19	20	22	22	19	18	18	20	21
Cu	24	26	29	25	26	30	21	46	44	28	27	22	24	24	22	28	22	23	44
Zn	127	126	126	126	128	126	128	119	131	134	126	128	125	128	124	130	129	125	122
ppm (ICP-MS)																			
La	26.91	27.22	26.33	26.25	26.15	26.76	26.13	24.58	22.71	26.00	26.01	26.20	25.90	26.12	26.29	26.95	26.89	26.03	23.88
Ce	55.74	56.23	54.61	54.37	54.54	55.66	54.54	50.19	46.74	54.75	54.24	54.66	54.21	54.99	55.28	56.23	56.01	54.43	49.59
Pr	7.47	7.53	7.29	7.28	7.26	7.42	7.33	6.71	6.42	7.37	7.31	7.35	7.27	7.36	7.42	7.51	7.50	7.27	6.53
Nd	35.95	35.97	35.04	35.20	34.95	35.73	35.06	31.83	30.91	35.31	35.06	35.13	35.10	35.44	35.69	36.21	35.99	34.95	31.03
Sm	9.72	9.76	9.45	9.44	9.40	9.57	9.51	8.60	8.50	9.51	9.48	9.48	9.45	9.55	9.63	9.70	9.71	9.37	8.40
Eu	3.92	3.97	3.85	3.79	3.74	3.81	3.75	3.23	3.25	3.82	3.86	3.82	3.78	3.83	3.78	3.83	3.87	3.71	3.16
Gd	10.18	10.07	9.84	9.91	9.90	10.08	9.95	9.02	8.84	9.93	9.85	9.80	9.78	9.88	10.06	10.21	10.16	9.93	8.80
Tb	1.57	1.59	1.53	1.55	1.54	1.59	1.55	1.43	1.41	1.54	1.54	1.53	1.54	1.58	1.58	1.62	1.61	1.55	1.40
Dy	9.61	9.64	9.25	9.30	9.33	9.59	9.34	8.66	8.58	9.22	9.23	9.25	9.18	9.41	9.41	9.66	9.61	9.31	8.45
Ho	1.92	1.92	1.86	1.88	1.86	1.91	1.89	1.78	1.75	1.85	1.86	1.85	1.87	1.88	1.91	1.93	1.93	1.87	1.72
Er	5.06	5.07	4.93	4.92	5.01	5.03	4.92	4.72	4.62	4.90	4.88	4.86	4.90	5.04	5.02	5.09	5.12	4.94	4.62
Tm	0.70	0.70	0.69	0.69	0.69	0.70	0.70	0.67	0.65	0.68	0.68	0.68	0.69	0.70	0.70	0.71	0.70	0.69	0.64
Yb	4.23	4.31	4.16	4.17	4.20	4.25	4.24	4.11	4.00	4.09	4.13	4.15	4.13	4.18	4.29	4.35	4.28	4.16	3.96
Lu	0.65	0.66	0.64	0.64	0.64	0.65	0.65	0.63	0.62	0.64	0.63	0.64	0.64	0.66	0.66	0.67	0.68	0.65	0.62
Ba	2463	2218	2156	1997	1903	1924	1882	1547	1538	2405	2368	2146	2043	1956	1955	2034	2066	1925	1545
Th	3.89	3.99	3.92	3.88	3.93	4.06	4.00	4.04	3.55	3.92	3.94	3.99	3.99	4.06	4.11	4.17	4.23	4.11	4.18
Nb	7.32	7.48	7.34	7.34	7.23	7.56	7.35	7.27	6.31	6.74	6.67	6.43	6.98	7.02	7.22	6.63	6.51	6.75	7.11
Y	49.81	50.03	48.70	48.79	49.16	49.72	49.14	46.55	44.61	47.43	47.66	47.80	47.71	49.16	49.61	50.53	50.43	48.59	45.50
Hf	4.06	4.12	4.04	4.03	4.05	4.16	4.08	3.99	3.77	3.93	3.95	3.93	3.98	4.09	4.09	4.12	4.08	4.02	3.99
Ta	0.48	0.49	0.48	0.48	0.46	0.49	0.48	0.46	0.41	0.44	0.43	0.40	0.45	0.46	0.46	0.43	0.40	0.42	0.46
U	1.33	1.37	1.32	1.35	1.34	1.39	1.36	1.42	1.27	1.41	1.38	1.40	1.41	1.43	1.45	1.48	1.50	1.44	1.48
Pb	6.40	6.58	6.47	6.41	6.32	6.57	6.48	6.61	5.90	6.30	6.29	6.44	6.35	6.47	6.59	6.72	6.80	6.61	6.71
Rb	40.1	41.2	42.0	41.9	40.2	41.2	39.0	40.5	38.8	42.0	43.0	41.0	39.5	41.2	40.8	44.5	43.8	41.5	41.7
Cs	1.94	1.66	1.67	1.72	1.55	1.62	1.57	1.69	1.45	1.81	1.73	1.42	1.43	1.66	1.52	2.29	2.33	1.64	1.66
Sr	425	419	406	416	420	421	419	399	389	421	405	413	407	428	421	431	436	415	407
Sc	38.5	39.1	39.4	40.3	40.1	40.7	40.8	39.6	42.9	39.2	38.6	39.8	40.3	40.8	40.6	40.7	41.4	40.2	40.0
Zr	138	142	138	139	139	143	140	140	129	135	136	138	138	141	143	144	144	141	140

Note: BrRCC2a—clast from block-and-ash-flow layer in plagioclase-andesite breccia; BrRCC3d—clast in plagioclase-andesite breccia at modern Red Clover Creek floor; BrfRCC6—clast from flow-front breccia in plagioclase-andesite breccia; BrRCC10a—clast from hornblende-andesite breccia; TbrRCC1—clast from landslide megabreccia; TbrRCC2—clast from landslide megabreccia. The identification (ID) for all Red Clover Creek samples is the flow number prefaced by 02LJ. The ID for all Stony Ridge samples is the flow number prefaced by 03LJ. Analyses for all samples were conducted at Washington State University: 27 major and trace elements were analyzed by low (2:1) Li-tetraborate fused bead technique X-ray fluorescence (XRF); 26 elements, including all 14 naturally occurring rare earth elements, were analyzed by inductively coupled plasma–mass spectrometry (ICP-MS).

†Denotes value >120% of the highest laboratory standard.

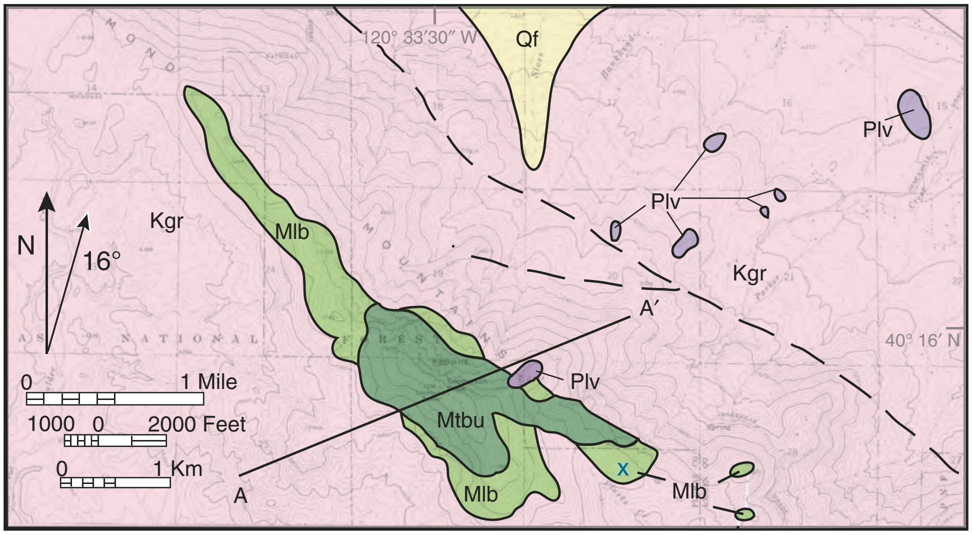


Figure 7. Geologic map of Thompson Peak (mapping by Grose and Porro, 1989; modified by Garrison, 2004). Map legend is same as Figure 3.

may be as much as 120 m thick at Putnam Peak; however, he included talus of the basalt below the lowest exposure of outcrop in his estimation of the unit's thickness, so the actual flows may be thinner at this location.

PHYSICAL VOLCANOLOGY OF THE LOVEJOY BASALT

The vent-proximal facies of the Lovejoy basalt (Stony Ridge and Red Clover Creek) flowed through a paleocanyon cut into basement rocks, while the vent-distal facies (ancestral Sacramento Valley) spread out and ponded on the floor of a broad basin (Fig. 1B). We have not yet studied the medial facies, but its distribution and descriptions by previous workers (e.g., Durrell, 1959b; Doukas, 1983; Hamilton and Harlan, 2002) indicate that these flows were also funneled through one or more paleocanyons. At all localities, the Lovejoy basalt is characterized by its distinctive ink-black appearance, which is the result of a relatively high glass content (up to 30%–40%). There do not appear to be physical characteristics of the Lovejoy basalt that differentiate one flow from another, or allow for correlation of individual flows between different principal erosional remnants, other than the presence of phenocrysts in the uppermost flow in the vent-proximal facies. We speculate that the vent-proximal facies were emplaced by open-channel flow, since it appears to lack recognizable lava tubes, suggesting that the basalt may have erupted at a relatively high temperature, or with high effusion rates, or both. This is consistent with the paleomagnetic data, which indicate very rapid eruption of the basalt (Coe et al., 2005).

The overall organization of individual Lovejoy basalt flows appears to conform well to the model of internal structures of flow lobes within continental flood basalt provinces presented by Self et al. (1997) as divided into a sparsely vesicular basal zone, a lava core exhibiting well-developed columnar jointing, and a highly vesicular, irregularly jointed upper crust (Fig. 5). These features appear to be common to basalt flows at a wide variety of localities and over a wide range of flow volumes (e.g., Iceland, Hawaii, Columbia River basalts). The percentage of each flow thickness that makes up the core in the Lovejoy basalt appears to vary from 70% to <25%. We attribute this wide variation to the fact that the proximal flows in the northern Sierra Nevada were emplaced over a variable and often steep topography.

The majority of the Lovejoy basalt flows in vent-proximal locations exhibit a highly vesicular upper section, and the upper crust generally erodes to a talus slope of debris showing up to 30%–40% vesicles. Self et al. (1997) observed that the upper

Figure 8. Vent-proximal deposits (scoria) in the Lovejoy basalt at Thompson Peak.

crust in the Roza flows is characterized by a similarly high vesicularity, and concentrations of vesicles have also been identified in the upper crust of pahoehoe flows at Kilauea Volcano in Hawaii (Cashman et al., 1999; Kauahikaua et al., 2003). The shape and connectivity of vesicles in basalt lava flows can be used to identify the morphology of the flow as either pahoehoe (with generally spherical or ellipsoidal, smooth vesicles that tend to remain isolated from each other) or ‘a’ā (with irregularly shaped, jagged, and commonly highly interconnected vesicles) (Cashman et al., 1999). The vesicles in the Lovejoy basalt tend to be spherical or ellipsoidal, and not well connected, consistent with the lack of an observed ‘a’ā crust.

Where the Lovejoy basalt began to pond and spread into the ancestral Sacramento Valley, its upper surface is marked by a series of generally N-S–trending, gently rolling, up to meter high, alternating ridges and swales that may extend for hundreds of meters or more (Fig. 9). These ridges form a smooth undulating surface at both North and South Table Mountains, with wavelengths of ~5–8 m. The ridges and swales do not appear to correspond to any jointing or fracture pattern in the basalt. We interpret these features to be compressional ridges that formed as the basalt flowed out from canyons in the mountains onto a shallower gradient in the ancestral Sacramento Valley and began to pond and inflate. The size of the compressional ridges is more typical of silicic flows, but it is consistent with the greater thicknesses of ponded flows in the ancestral Sacramento Valley (75 m or more), since fold wavelengths are roughly proportional to the thickness of a flow’s cooled upper carapace (Fink and Fletcher, 1978; Gregg et al., 1998; Fink and Anderson, 1999). Similar ridge features have been observed in basaltic lava flows on Mars that are interpreted to have been emplaced in flood-style eruptions (Thelig and Greeley, 1986).

The Lovejoy basalt is interpreted to have flowed a minimum distance of ~240 km from its source vent at Thompson Peak to reach Putnam Peak (Fig. 1B). This suggests that the Lovejoy basalt was highly fluid and well-insulated in order to flow for such an extended distance without solidifying. It is unlikely that the basalt would have been able to travel as open-channel flow for such a great distance without cooling to the point of stagnating, and so it was likely at least partly fed by injections of lava transported through lava tubes. Flows of the Roza flow field traveled hundreds kilometers from their source vents, and Self et al. (1997) proposed that the Roza flows, as well as other flows in the Columbia River Basalt Group, formed

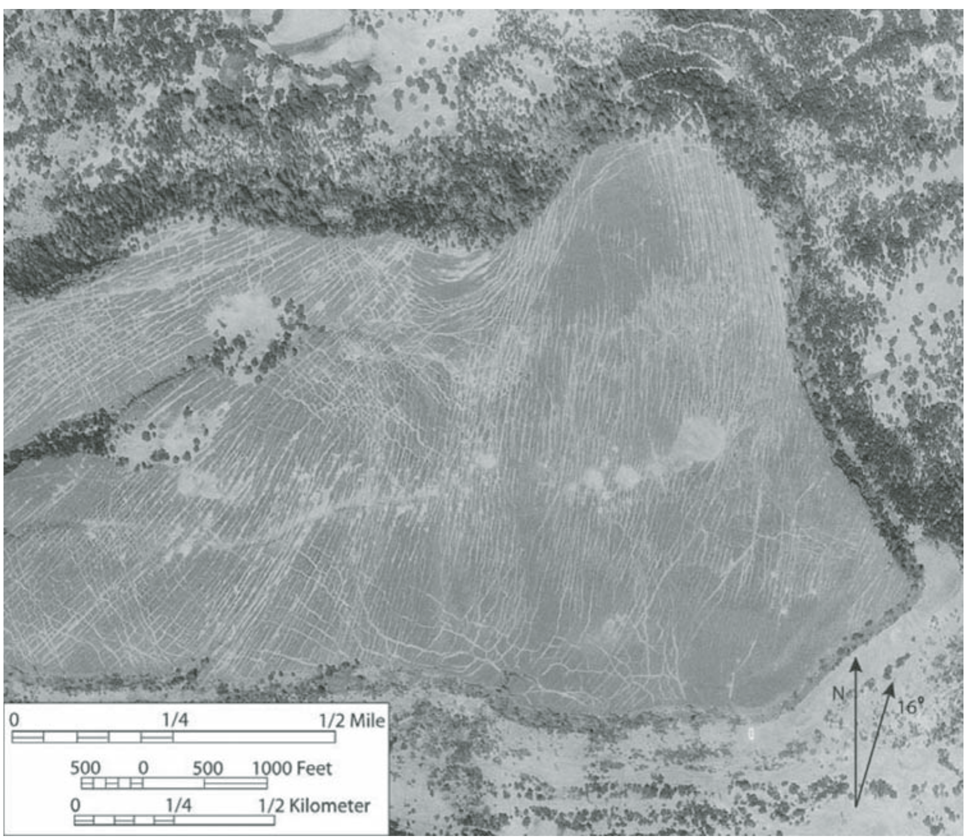


Figure 9. Aerial photograph of the topographic high formed by the Lovejoy basalt at South Table Mountain, near Oroville, California. The linear pattern on the surface of the basalt is interpreted to represent pressure ridges formed as the basalt spread into the ancestral Sacramento Valley. (Photograph courtesy U.S. Geological Survey.)

as inflationary pahoehoe sheets over extremely shallow gradients, estimated at ~0.1% (0.05°). They have not identified lava tubes in flows of the Columbia River basalts, but they state that it is unlikely that lava tubes would have drained to leave remnant cylindrical channels on the shallow slopes the Roza flows were emplaced on. Lava feeder tubes for Hawaiian basalts on relatively flat ground have been shown to remain full or overpressured during the course of an eruption, as opposed to tubes on steeper terrain, which may develop headspace or downcut their base (Kauahikaua et al., 2003). Kauahikaua et al. (1998) also showed that lava tubes on steeper gradients proximal to the Pu‘u O‘o vent have a significantly higher aspect ratio (height to width of up to 1:1) than distal ones on low gradients (one:several tens of meters). High-aspect-ratio lava tubes should be recognizable in laterally extensive outcrops of the vent-proximal facies of the Lovejoy basalt, but they are absent. This may indicate that the vent-proximal facies was emplaced in a paleocanyon characterized by low axial gradients, or that it was emplaced by open-channel flow.

The source vent for the Lovejoy basalt at Thompson Peak is located 2000 m above and 120 km distant from South Table Mountain at the edge of the Sacramento Valley. This corresponds to an average grade of ~1.65% (0.95º) in the present-day setting, and localized sections of the paleocanyon(s) through which the Lovejoy basalt flowed may have been more steeply sloped. It remains controversial whether Miocene canyon gradients in the Sierra Nevada may have been significantly lower or higher than at present (Stock et al., 2003; House et al., 1998), but it is highly unlikely that they were as gentle as the depositional slope for the Columbia River Basalt Group. If the Lovejoy basalt flowed over a relatively gentle grade, it may have prevented feeder tubes from draining to leave remnant pathways. This is likely the case where the basalt ponded in the ancestral Sacramento Valley, but the apparent lack of lava tubes in vent-proximal paleocanyons may indicate open-channel flow. The development of a dense lava core and vesicular crust in the basalt could have resulted from its being emplaced proximally as a sequence of open-channel fluid flows that stagnated and cooled rapidly after an abrupt termination of each eruptive event.

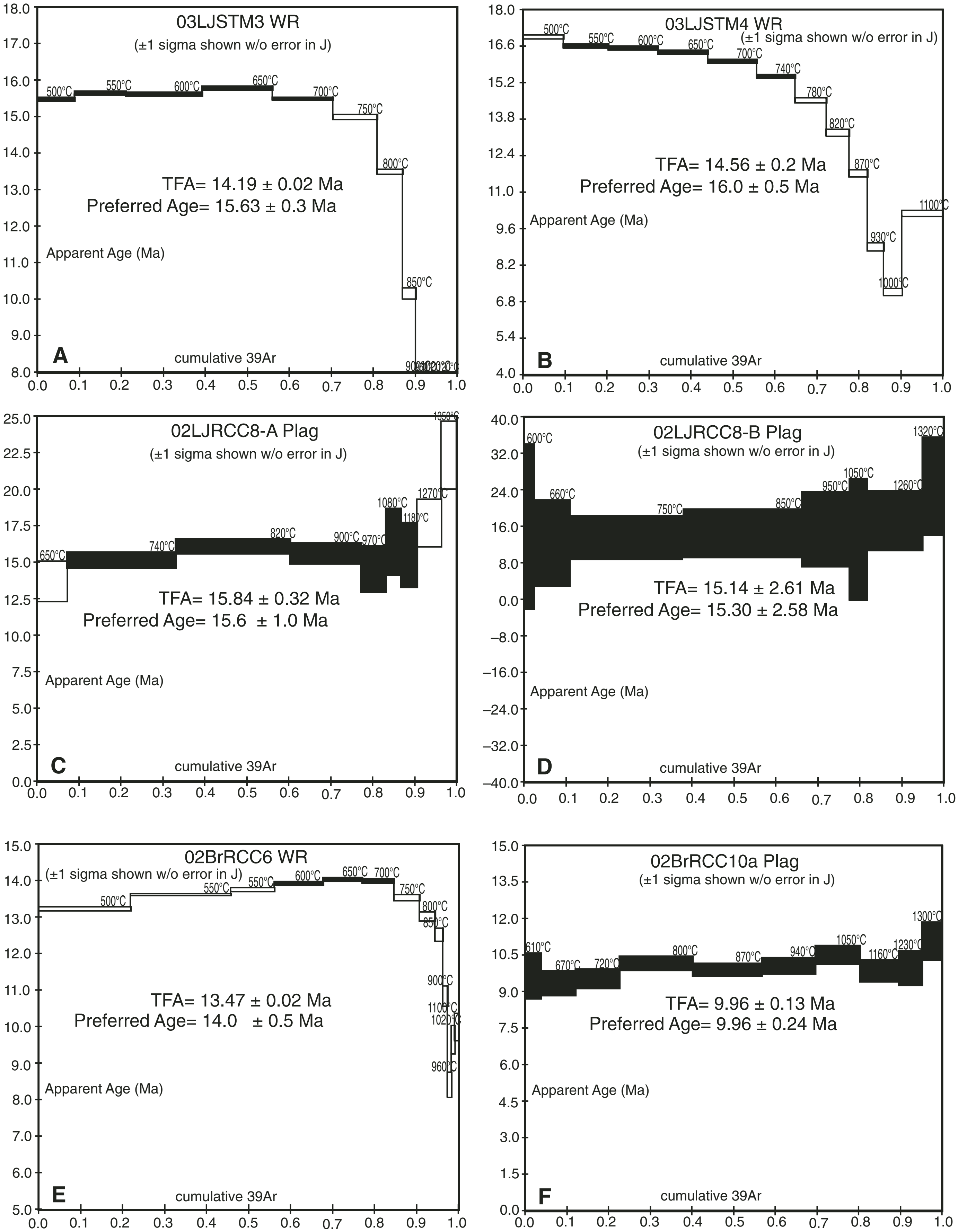
RADIOMETRIC DATING OF THE LOVEJOY BASALT AND OVERLYING STRATA

The age of the Lovejoy basalt has been widely disputed since its designation as a formation. The basalt is extremely fine grained, consisting almost entirely of groundmass microcrystalline plagioclase and olivine with a high percentage of altered glass that composes up to 30%–40% of the rock. This renders the basalt highly susceptible to argon loss by weathering, hydration of the glass, and alteration to clay minerals, which may account for the wide spectrum of previously reported K-Ar dates. In addition, the extremely small size (~10 µm) of the crystalline phases in the groundmass makes them highly susceptible to reactor-induced recoil.

The University of California at Santa Barbara (UCSB) Argon Laboratory has obtained $^{40}Ar/^{39}Ar$ step-heating spectra for a total of five samples of the Lovejoy basalt, and one sample each of the overlying plagioclase-andesite breccia and hornblende-andesite breccia (Fig. 10; Table 2). The analyzed rocks include three whole-rock samples collected from Red Clover Creek and South Table Mountain, and two samples of plagioclase separates collected from the uppermost flow of the Lovejoy basalt at Stony Ridge and Red Clover Creek. Due to the glass content and fine-grained character of the basalt, the whole-rock sample from Red Clover Creek shows a high degree of error in age between steps, at best placing it as mid-Miocene. The samples collected from South Table Mountain are slightly coarser grained and show a higher degree of crystallinity than those collected from Red Clover Creek, possibly due to the basalt ponding at this location and cooling over a longer period of time. The whole-rock sample 03LJSTM4 showed a steep decline in calculated age at higher percentages of cumulative Ar released, possibly due to Ar loss by recoil during irradiation (Fig. 10). However, sample 03LJSTM3 returned a relatively good plateau, which yielded a date of 15.63 ± 0.3 Ma (Fig. 10). The plateau shows an error between heating steps of greater than 2σ, so it is statistically not meaningful, but it does allow for interpretation of a preferred age for the sample.

A second problem arises for dating plagioclase separates collected from the upper flow of the Lovejoy basalt at both Red Clover Creek and Stony Ridge. Plagioclase in the Lovejoy basalt is highly calcic; K/Ca ratios in the plagioclase are ~0.003. This leaves the interpreted results highly susceptible to mass discrimination corrections, Ca-derived interference corrections, and tailing corrections. The correction factors involving Ca-derived isotopes for samples with a K/Ca ratio this low are so great that the analytical results are practically meaningless. The large margin of error in the apparent age for each heating step of sample 02LJRCC8 (Fig. 10), as with the whole-rock samples from South Table Mountain, represents analytical interpretation of a preferred age, but the estimates between 15.3 ± 2.58 Ma to 15.6 ± 1.0 Ma (02LJRCC8) and 15.12 ± 4.64 Ma (03LJSR13, see Table 2) roughly agree with the range of dates obtained for the Lovejoy basalt by previous researchers and the new date obtained by whole-rock analysis. Two calculated ages were obtained for sample 02LJRCC8 (Fig. 10); this sample

Figure 10. $^{40}Ar/^{39}Ar$ step-heating spectra for whole-rock samples of the Lovejoy basalt at South Table Mountain: (A) LJSTM3 and (B) LJSTM4. (The plateau for LJSTM3 shows an error between steps of greater than 2σ, so the calculated age of 15.63 ± 0.3 Ma reflects a preferred analytical interpretation and estimated error.) $^{40}Ar/^{39}Ar$ step-heating spectra for whole-rock samples plagioclase separate from the uppermost flow of the Lovejoy basalt at Red Clover Creek (LJRCC8) at two different postirradiation decay times for the sample to reduce the tailing effect of ^{37}Ar into the ^{36}Ar peak: (C) 3 mo and (D) 6 mo. $^{40}Ar/^{39}Ar$ step-heating spectra for samples of (E) the plagioclase-andesite breccia (BrRCC6) and (F) the hornblende-andesite breccia (BrRCC10a) at Red Clover Creek.


03LJSTM3 WR
(±1 sigma shown w/o error in J)
TFA= 14.19 ± 0.02 Ma
Preferred Age= 15.63 ± 0.3 Ma
Apparent Age (Ma)
cumulative 39Ar
A
03LJSTM4 WR
(±1 sigma shown w/o error in J)
TFA= 14.56 ± 0.2 Ma
Preferred Age= 16.0 ± 0.5 Ma
Apparent Age (Ma)
cumulative 39Ar
B
02LJRCC8-A Plag
(±1 sigma shown w/o error in J)
TFA= 15.84 ± 0.32 Ma
Preferred Age= 15.6 ± 1.0 Ma
Apparent Age (Ma)
cumulative 39Ar
C
02LJRCC8-B Plag
(±1 sigma shown w/o error in J)
TFA= 15.14 ± 2.61 Ma
Preferred Age= 15.30 ± 2.58 Ma
Apparent Age (Ma)
cumulative 39Ar
D
02BrRCC6 WR
(±1 sigma shown w/o error in J)
TFA= 13.47 ± 0.02 Ma
Preferred Age= 14.0 ± 0.5 Ma
Apparent Age (Ma)
cumulative 39Ar
E
02BrRCC10a Plag
(±1 sigma shown w/o error in J)
TFA= 9.96 ± 0.13 Ma
Preferred Age= 9.96 ± 0.24 Ma
Apparent Age (Ma)
cumulative 39Ar
F

was allowed to undergo different decay times after irradiation (3 months and 6 months) to reduce the tailing effects of ^{37}Ar on the ^{36}Ar peak. The age of 15.3 ± 2.58 Ma (Fig. 10) represents a longer decay period after irradiation, and therefore the analysis was much less susceptible to effects of the tailing correction. The large margins of error in age for each individual heating step in this spectrum represent a decay correction and not tailing or mass discrimination corrections. While difficult to constrain better, the sample returned a good plateau, and the restricted ranges of error between individual steps indicate that the age of the Lovejoy basalt is likely not at the lower or upper limits of the given preferred age.

The results for the Lovejoy basalt show large uncertainties due to the large amount of altered glass present and the high-Ca/low-K content of the basalt. However, the Lovejoy basalt is unequivocally mid-Miocene in age and broadly coeval with the main phase of the Columbia River Basalt Group.

We also obtained $^{40}Ar/^{39}Ar$ step-heating spectra for samples from the overlying breccias at Red Clover Creek. The sample from an inferred flow-front breccia within the plagioclase-andesite breccia (Fig. 10, 02BrRCC6) returned a relatively poor plateau that showed effects of Ar loss at low-temperature steps and reactor-induced recoil at high-temperature steps. The preferred age for the breccia is given as 14.0 ± 0.5 Ma; however, there is a large degree of uncertainty for this age. The clast from the hornblende-andesite (Fig. 10, 02BrRCC10a), however, returned a good plateau with little error between any heating steps, and the preferred age of 9.96 ± 0.24 Ma is in good agreement with the given total fusion age of 9.96 ± 0.13 Ma.

GEOCHEMISTRY OF THE LOVEJOY BASALT

We present new geochemical data and analyses for the Lovejoy basalt in order to further assess its correlation with the Columbia River Basalt Group. Samples from 11 of the 13 flows at Stony Ridge, the eight flows at Red Clover Creek, and samples from Thompson Peak and South Table Mountain were analyzed for major- and trace-element concentrations by X-ray fluorescence (XRF) and inductively coupled plasma-mass spectroscopy (ICP-MS). Samples from Black Butte and Putnam Peak were additionally analyzed by XRF (Table 3).

The Lovejoy basalt is remarkably homogeneous, both between flows and with distance from the source vent. The uppermost, plagioclase-phyric flow is depleted in many trace elements as well as P_2O_5, K_2O, and TiO_2, relative to the other flows, and enriched in Ni, Cr, and Cu, as is flow 1 at Stony Ridge (Table 3). The basalt also has an anomalously high amount of Ba, ranging in concentration at Stony Ridge from 1538 ppm in flow 1, to 2405 ppm in flow 2 (Table 3). The Lovejoy basalt otherwise displays little chemical variation.

The Lovejoy basalt falls on the alkalic/subalkalic boundary of Irvine and Baragar (1971) and near the intersection of basalt, basaltic andesite, trachybasalt, and trachybasaltic andesite on a plot of total alkalis versus silica of Le Bas et al. (1986) (Fig. 11). If plotted on an alkali-ferromagnesian (AFM) diagram, the Lovejoy basalt is tholeiitic. In both the AFM and alkali-silica diagram, the Lovejoy overlaps compositions from contemporaneous Columbia River Basalt Group samples from the 16.1–15.0 Ma Imnaha basalt and Grande Ronde basalts (Fig. 12). In contrast, average sample compositions of low-MgO (3%–5%) High Cascade arc basalts and basaltic andesites from California, Oregon, and Washington plot in the calc-alkaline field. Tholeiitic basalts have been erupted from the Cascade arc; however, since the late Eocene, the arc has been dominated by this form of calc-alkaline volcanism (McBirney, 1978). Further, tholeiitic rocks in the modern Cascade arc tend to have >16% Al_2O_3 (Bacon et al., 1997), while the Lovejoy basalt contains 13.85%–14.47% Al_2O_3 (Fig. 13A), and Cascade arc rocks tend to have lower concentrations of FeO at a given SiO_2 content than the Lovejoy basalt (Fig. 13B).

Trace-element abundances of the Lovejoy basalt normalized to normal mid-ocean-ridge basalt (N-MORB) display an irregular or "spiked" pattern (Fig. 14). The pattern shows an enrichment of Ba (up to 2405 ppm), and a marked Nb trough. Both features are often indicative of a subduction-related source, although a relatively depleted concentration of Nb is not uncommon in intraplate tholeiites (Wilson, 1989). In the Lovejoy basalt, the Nb trough may be indicative of contamination of the source magma body by subduction-related melt. Enrichment of elements with low ionic potential, such as Ba, has been attributed to contamination by fluids released from subducting slabs (Wilson, 1989), but the concentration of Ba in the Lovejoy basalt is highly enriched in comparison with samples from the Cascade arc and the Columbia River Basalt Group and may reflect contamination of the Lovejoy basalt by a high-Ba crustal component, or variation in the mantle source region.

Although the Lovejoy basalt is more enriched in elements such as Ba, K, and P, the general trace-element patterns of the Lovejoy basalt compare well with trace-element patterns of Columbia River Basalt Group flows (Fig. 14). In contrast, when compared to the Lovejoy basalt and Columbia River Basalt Group lavas at similar MgO or SiO_2 contents, High Cascade arc basalts and basaltic andesites are less steep (i.e., lower Cs/La and lower La/Yb ratios) and have lower overall concentration levels (especially for heavy rare earth [HREE] and associated elements). The dissimilarity between the Lovejoy basalt and Cascade lavas and the affinity of the Lovejoy basalt with Columbia River Basalt Group basalts (i.e., its tholeiitic composition and evolution to a moderate to low SiO_2 at low MgO) indicate that the Lovejoy is not subduction related. Instead, the Lovejoy basalt appears to have followed an evolutionary path similar to flood basalts of the Pacific Northwest, perhaps with more significant crustal contamination, as suggested by the high levels of Ba and K. While the mantle source of the Lovejoy basalt is still uncertain, the similarities between the Lovejoy basalt and the Columbia River Basalt Group suggest a genetic relationship.

TABLE 3. $^{40}Ar/^{39}Ar$ STEP-HEATING DATA FOR THE LOVEJOY BASALT AND OVERLYING MIOCENE STRATA

Sample	Packet	Material†	Geological context	Exp. (step)	Preferred age (Ma)	Estimated ± 2σ	TFA	39p (%)	Isochron age	^{39i}Ar (%)	MSWD	$^{40}Ar/^{36i}Ar$	K/Ca	Radiogenic (%)
03LJSTM3	SB49-87	WR	Distal, coarse-grained flow at South Table Mountain	12	15.63	0.30	14.19	70	6.15 ± 4.62	70	1.19	949.5 ± 371.2	0.16–1.2	66–79
03LJSTM4	SB49-88	WR	Distal, coarse-grained uppermost flow at South Table Mountain	12	16.00	0.5	14.56	55	n/a	55	33.2	490.8 ± 223.6	0.19–0.83	47–50
02LJRCC8-A	SB49-90	plag	Uppermost flow of the Lovejoy basalt at Red Clover Creek	9	15.60	1	15.84	83	15.58 ± 0.82	83	0.21	295.6 ± 7.1	0.003–0.004	24–74
02LJRCC8-B	SB49-91	plag	Uppermost flow of the Lovejoy basalt at Red Clover Creek	8	15.30	2.58‡	15.14	100	11.87 ± 7.05	100	0.1	352.1 ± 40.9	0.003–0.004	23–56
03LJSR13	SB49-95	plag	Uppermost flow of the Lovejoy basalt at Stony Ridge	6	15.12	4.64‡	15.27	100	15.16 ± 8.66	100	0.07	294.6 ± 22.3	0.003–0.004	18–55
02BrRCC6	SB49-89	WR	Flow-front breccia clast in plagioclase-andesite breccia	13	14.00	0.5	13.47	29	14.09 ± 0.12	29	0.98	291.7 ± 4.5	0.14–3.1	52–75
02BrRCC10a	SB50-105	plag	Clast from hornblende-andesite breccia	10	9.96	0.24	9.96	100	9.94 ± 0.21	100	0.77	296.2 ± 4.4	0.12–0.15	28–71

Note: TFA—Total Fusion Age; MSWD—mean square of weighted deviates.
†WR—whole rock; plag—plagioclase.
‡Est. ± 1σ.

DISCUSSION: IMPLICATIONS FOR PLUME DYNAMICS

Our field geochronologic and geochemical data demonstrate two important findings, namely that the Lovejoy basalt is a mid-Miocene eruptive unit, and that it is temporally and compositionally correlative with the Columbia River Basalt Group. Comparisons of the Lovejoy with Cascade arc lavas show large differences in both major- and trace-element content and support the conclusion that the Lovejoy basalt is not derived from an arc source (Figs. 12, 13, and 14). Our new $^{40}Ar/^{39}Ar$ dates cluster at 15.4 Ma, which places the Lovejoy coeval with the 16.1–15.0 Ma Imnaha and Grand Ronde flows, and the 15.5–14.5 Wanapum flows (Camp and Ross, 2004).

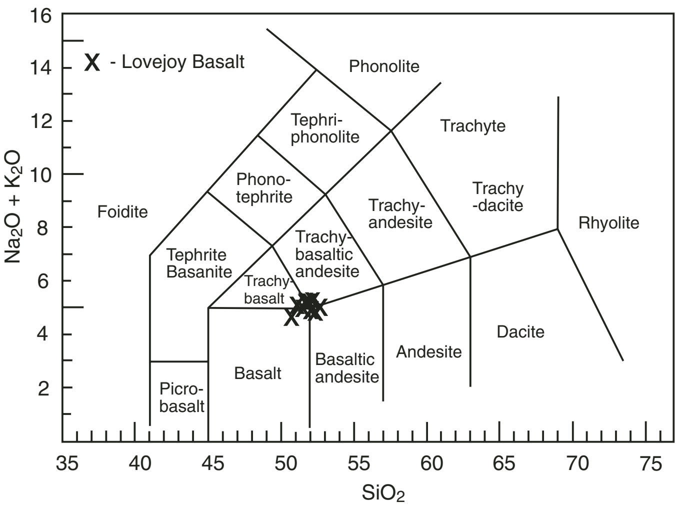
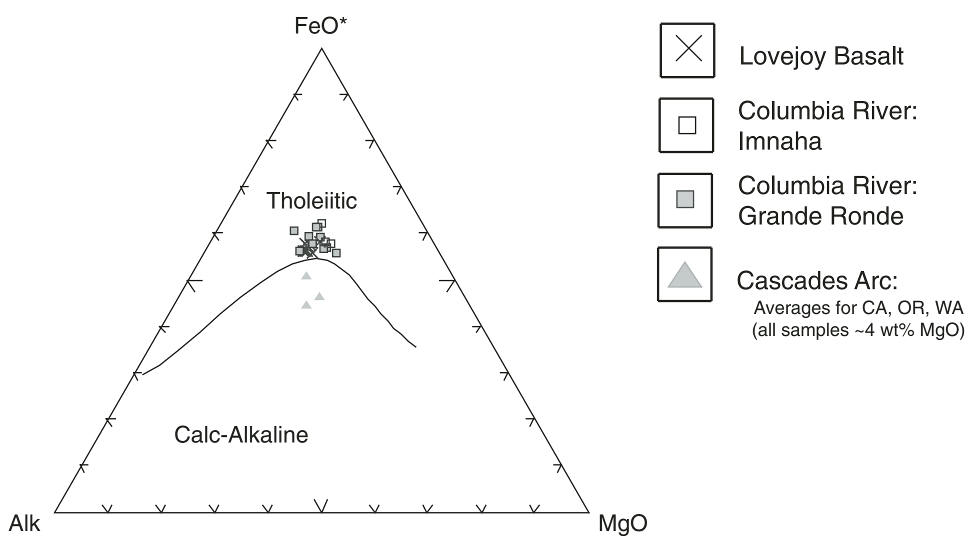


Figure 11. Chemical classification of the Lovejoy basalt using total alkalis versus silica of samples from Stony Ridge (diagram of Le Maitre et al., 1989).

The field and geochronologic data presented here, together with data from the region summarized by Busby et al. (2008, this volume), also support the new interpretation that the Lovejoy basalt erupted in a forearc position. Previous workers have drawn the boundaries of the "ancestral Cascades arc" in a swath that includes the central and northern Sierra Nevada as well as adjacent Nevada (Brem, 1977; Christiansen and Yeats, 1992; Dickinson, 1997). In western Nevada, andesites range from early Oligocene to late Miocene in age (e.g., Trexler et al., 2000; Garside et al., 2005; Castor et al., 2002). In contrast, in the Sierra Nevada andesite volcanism appears to have been restricted to the middle and late Miocene. Our new $^{40}Ar/^{39}Ar$ ages from the central and northern Sierra Nevada, taken together with mostly K/Ar ages reported from the literature, allow us to speculate that three pulses of calc-alkaline andesite volcanism may have occurred in the Sierra Nevada during the Miocene: at ca. 15–14 Ma, 10–9 Ma, and 7–6 Ma (Busby et al., 2008). The first two of these three pulses is recorded in the new dates presented here for the Red Clover Creek section. These dates indicate that the arc front shifted westward (trenchward) into the Sierra Nevada immediately after the Lovejoy basalt erupted there.

The association of the Lovejoy with mid-Miocene flood basalt volcanism has considerable implications for North



Columbia River Basalt data: Hooper and Hawkesworth, 1993
Steens/Malheur Gorge Basalt data: Camp et al., 2003
Cascade Arc data: GEOROC database
(http://georoc.mpch-mainz.gwdg.de/georoc/ [accessed November 2006])

Figure 12. AFM (Alkali-ferromagnesian) diagram comparing the Lovejoy basalt with Imnaha and Grande Ronde flows of the Columbia River Basalt Group and with average compositions of low-MgO (3%–5%) High Cascade arc basalts and basaltic andesites from California, Oregon, and Washington.

American plume dynamics. Either: (1) the Lovejoy represents a rapid migration of plume head material, at ~20 cm/yr, and in a direction not previously recognized, (2) the plume had a much greater spatial extent than previously understood, or (3) the plume head split into "plumelets," of which the Lovejoy is an example (Ihinger, 1994).

The first option seems most plausible given published arguments in favor of a plume hypothesis for the Columbia River Basalt Group and the timing of the Lovejoy eruption. Camp and Ross (2004) documented the radial distribution of dikes about the presumed plume head and used magmatic migration rates (r) to estimate radial spreading. Migration rates were classified by Camp and Ross (2004) as either "rapid", r = 10–100 cm/yr, or "moderate," r = 1–5 cm/yr. The Lovejoy basalt would represent a new, rapid, southwestward direction of plume propagation in the Camp and Ross (2004) model. Accepting a 16.6 Ma age for plume inception to the north of the McDermitt caldera (Camp and Ross, 2004), a 15.4 Ma age for the Lovejoy, and the current distance of the Lovejoy from the McDermitt region, a 19 cm/yr migration rate is implied. This rate would be increased to perhaps as much as 40 cm/yr if the Sierra microplate has drifted significantly northward since 15.4 Ma (Dixon et al., 2000), but would certainly not exceed the 100 cm/yr limit observed for other migration trends (Camp and Ross, 2004).

The argument in favor of the Lovejoy basalt representing a southern expression of the plume must be taken in the context of the complexities of the regional geology. Fee and Dueker (2004)

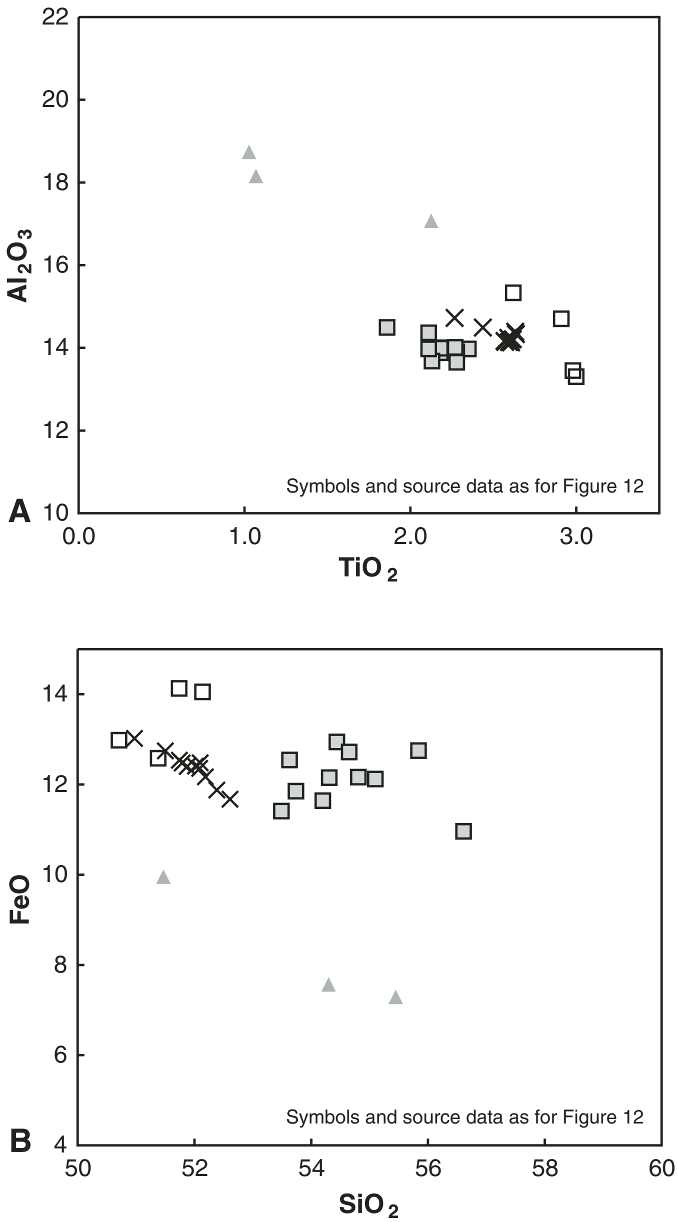


Figure 13. (A) Plot of Al_2O_3 versus TiO_2 and (B) plot of FeO versus SiO_2 for the Lovejoy basalt compared with flows of the Columbia River Basalt Group and average compositions of low-MgO High Cascade arc lavas.

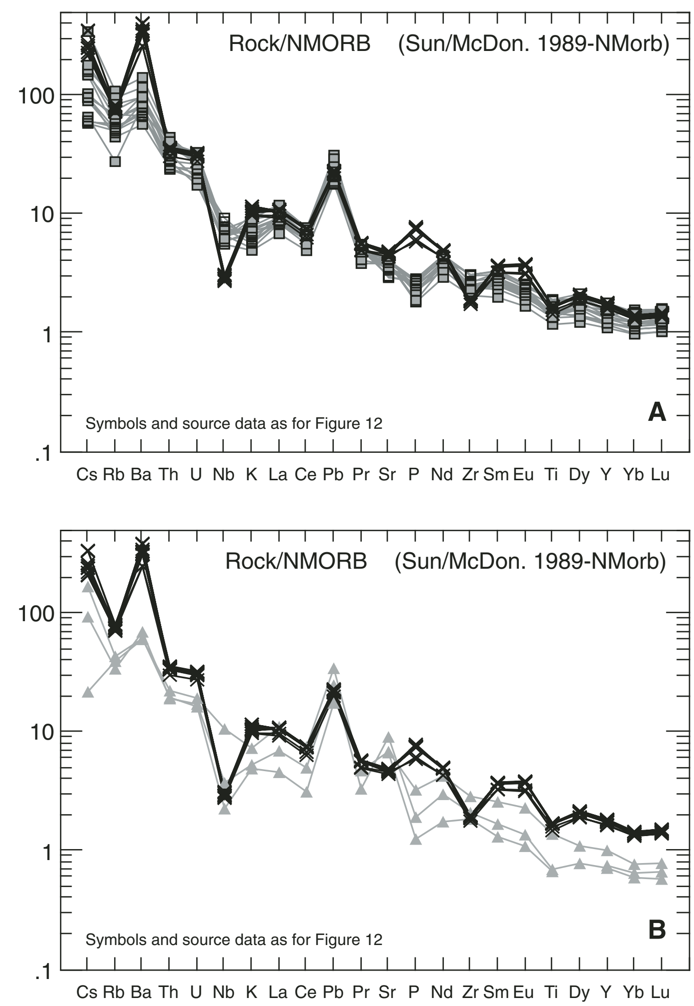


Figure 14. Trace-element concentrations normalized to normal mid-ocean-ridge basalt (N-MORB) for samples of (A) the Lovejoy basalt and the Imnaha and Grande Ronde basalts, and (B) the Lovejoy basalt and average compositions of low-MgO High Cascade arc lavas.

and Waite et al. (2005, 2006) showed that beneath Yellowstone, the 410 km discontinuity is deflected by a magnitude sufficient to warrant a significant (200 °C?) thermal anomaly in the transition zone, and that an upper mantle plume is therefore plausible, if not likely. However, the Columbia River basalts and the Snake River Plain basalts show significant differences in composition and isotopic character that might not be adequately explained by varying liquid lines of descent or crustal contamination (Chamberlain and Lambert, 1994). Further complicating the regional picture and plume model is the presence of the Newberry melting anomaly, a chain of silicic volcanic centers that young westward across the High Lava Plains province in Oregon, away from the McDermitt caldera and Yellowstone hotspot track (Christiansen et al., 2002). Alternate hypotheses for extensive mid-Miocene volcanism include tectonism related to development of the Pacific–North American plate boundary (Dickinson, 1997), and partial melting due to upper-mantle convection enhanced by lithospheric controls (Humphreys et al., 2000; Christiansen et al., 2002). However, Camp and Ross (2004) noted flaws with the alternatives to the plume model and provided a viable model to explain migrating patterns of magmatism. The Lovejoy basalt compounds some of the problems with the alternatives to the plume model.

There is the possibility that either the plume head area was simply greater than has been previously recognized, or that the Lovejoy basalt is the result of a "plumelet" detached from a larger thermal upwelling (e.g., Ihinger, 1994; Schubert et al., 2004). However, in either case, the correlation of the Lovejoy basalt with the Columbia River Basalt Group undermines the argument that the mid-Miocene melting anomaly in Oregon and Washington was caused solely by lithospheric extension and passive upwelling, with magmatism focused along pre-existing fractures (Humphreys et al., 2000; Christiansen et al., 2002), and not by a mantle thermal anomaly. It seems unlikely that a pre-existing lithospheric flaw would be continuous across Precambrian basement, transitional lithosphere, and accreted oceanic terranes, and then into the Sierra Nevada microplate to the location of the Lovejoy basalt. Further, the southerly position of the Lovejoy basalt appears inconsistent with models that explain the northerly position of the Columbia River Basalt Group with respect to the Yellowstone hotspot track as the subduction-induced northward deflection of the plume head (Geist and Richards, 1993). As a result, the Lovejoy basalt is problematic for at least one model connecting the Columbia River Basalt Group to the Yellowstone hotspot track. A "plumelet" model might obviate the need for a new explanation regarding the northerly position of the Columbia River Basalt Group, but such a hypothesis is clearly ad hoc. We suggest, however, that the mantle plume and "lithospheric control" are not mutually exclusive hypotheses: the magmatic activity above a mantle plume can be just as easily controlled by lithospheric flaws as can the activity due to passive upwelling, and the Columbia River Basalt Group may well have been focused northward by such a process. Regardless, the recognition of the Lovejoy basalt as the southern extension of mid-Miocene flood basalt activity appears to strengthen the "thermal point source" explanation, as provided by the mantle-plume hypothesis, although that "point" has now been broadened to encompass California. This scenario will likely require a reconsideration of plume dynamics models in western North America.

CONCLUSIONS

The Lovejoy basalt erupted from a vent at the present-day Thompson Peak, located west of Honey Lake in the Diamond Mountains, during the mid-Miocene period. The vent is identifiable by proximal volcanic deposits, including scoria, agglutinate, and bomb fragments, present along the majority of the ridge of basalt, which forms a relict spatter rampart. Available age data show that the vent was located in a forearc position, in contrast with the flood basalts of Oregon and Washington, which erupted in a backarc setting.

We have mapped unconformable contacts between the Lovejoy basalt and overlying Miocene strata at the type locality, and we interpret them as resulting from emplacement of younger units over a complicated paleotopography created by fluvial erosion of the Lovejoy basalt. In contrast to the previous interpretations of Durrell (1959a), we see little evidence of syndepositional faulting or significant postdepositional faulting at the type locality, and instead we propose that erosion of the basalt created a steep-sided paleocanyon with locally undercut walls that was filled by later andesitic mudflows.

The age of the Lovejoy basalt has been widely disputed since its designation as a formation. The basalt is highly susceptible to argon loss from weathering, hydration of glass in the groundmass, and alteration to clay minerals due to its fine grained character; the basalt's groundmass consists nearly entirely of microcrystalline plagioclase and olivine with up to 30–40% altered glass. This renders the basalt highly susceptible to argon loss by weathering, hydration of the glass and alteration to clay minerals. However, we have obtained $^{40}Ar/^{39}Ar$ step-heating spectra for a total of five samples of the Lovejoy basalt, which cluster near 15.4 Ma and suggest that it is coeval with the 16.1–15.0 Ma Imnaha and Grande Ronde flows and 15.5–14.5 Wanapam flows of the Columbia River Basalt Group. Moreover, the Lovejoy basalt appears to be geochemically dissimilar to Cascade arc lavas and does not appear to be subduction related. Instead, the trace-element patterns of the Lovejoy compare well with those from the Columbia River Basalt Group, except that the Lovejoy has much higher levels of P_2O_5, Ba, and K_2O, the latter two of which may indicate greater degrees of crustal contamination. While the mantle source of the Lovejoy basalt is uncertain, the affinity of the Lovejoy basalt to Columbia River Basalt Group basalts suggests a possible genetic relationship.

The recognition of the Lovejoy as the southern extension of mid-Miocene flood basalt volcanism has considerable implications for North American plume dynamics. We posit that the Lovejoy basalt represents a rapid migration of material from the Yellowstone mantle plume head in a direction not previously recognized, ~20 cm/yr to the south-southwest.

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